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**研究課題名（和文）** Probing THz Evanescent Waves of Non-equilibrium Dynamics

**研究課題名（英文）** Probing THz Evanescent Waves of Non-equilibrium Dynamics

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**研究成果の概要（和文）：**ナノデバイスにおける電荷キャリアの非平衡ダイナミクスを検出することは、何十年もの間依然として課題である。この問題を解決するため、本研究ではパッシブTHz散乱型近接場顕微鏡を用いて観測の実現を目指した。
グラフェン試料では、過剰ノイズによる表面付近の電磁エバネッセント波をイメージングした。金属試料では、電流による熱励起エバネッセント波を得た。GaAs半導体試料では、非線形領域において狭窄領域から伸びる近接場信号が検出されており、ホットエレクトロンのエネルギー散逸に起因すると考えられる。以上から，開発したTHz近接場顕微鏡が、デバイス産業および新規材料研究へ応用することが期待できる。

**研究成果の概要（英文）：**Detecting non-equilibrium dynamics of charge carrier in nano-device has remained to be a challenge for decades. To solve this technical issue, we used a passive THz scattering-type scanning near-field microscope (SNOM) to realize the detection.
In the graphene device, we imaged excess noise by probing electromagnetic evanescent waves (~20 THz) near the surface. In the metallic device, we imaged thermally excited evanescent wave. According to the simulation, the near-field intensity is consistent with the simulation of the current density distribution. The detected hot-position is due to the current-crowding effect. In GaAs semiconductor device, the near-field signal extending out of the constriction region was detected in non-linear region. This result originates from energy dissipation of hot electron. To sum up, the THz SNOM is proved to be powerful equipment for studying carrier dynamics in nano-device and expected for application in device industry and novel material study.

**研究分野：** Terahertz microscopy

**キーワード：** Near-field microscopy　THz image　Noise image　Graphene　Current crowding effect

## １．研究開始当初の背景

Most of the materials are covered by electromagnetic (EM) evanescent waves in the infrared/THz spectrum at finite temperature. The EM evanescent waves mainly originate from motion of charges. Therefore, we can study the charge dynamics by detecting the EM evanescent waves. Recently, our group has developed an ultra-high sensitivity THz near-field microscope and realized thermal excited evanescent waves imaging on metal and dielectric surface at room temperature at the nanoscale. Up to now, the measurements were carried out in thermal equilibrium state. However, we still interested in imaging the near-field signals while the sample is in non-equilibrium state, which could reveal the charge dynamics when they get further energy.

## ２．研究の目的

The passive THz scattering near-field optical microscope (s-SNOM) is a good candidate for visualizing non-equilibrium carrier dynamics at the nanoscale resolution. For instance, when charge carriers are passed through a device, the non-equilibrium carrier dynamics will induce excess near-field signals. According to the strength of the near-field signals, we can understand the energy dissipation/storage of the charge carriers. If this technique was established, the THz near-field microscopy cannot only be applied for examining electronic device, industrially, but also studying ballistic conductance, physically.

## ３．研究の方法

The passive THz s-SNOM we used here has the following unique advantages for imaging the device at the nanoscale: (1) Ultrahigh sensitivity THz detector with detection wavelength of 14.5 μm and detectivity of $1.2\times10^{15}$ cmHz$^{1/2}$/W. (2) Tip-height modulation of an AFM probe. (3) Ultrahigh spatial resolution (several tens of nanometers). (4) External light source is unnecessary. To bias the samples, an electrotransport measurement system was introduced into the s-SNOM, and the current modulation technique was also established.

The epitaxial graphene devices, NiCr narrow wire devices, and GaAs two-dimension electron gas (2DEG) devices were prepared by e-bean lithography fabrication technique.

The non-equilibrium EM evanescent waves were driven by dc or ac bias current and scattered by tungsten tip with a tip radius of about 50 nm. The tip was placed close to the sample surface (~ 5 nm). The scattered photons were detected by the THz confocal microscope.

## ４．研究成果

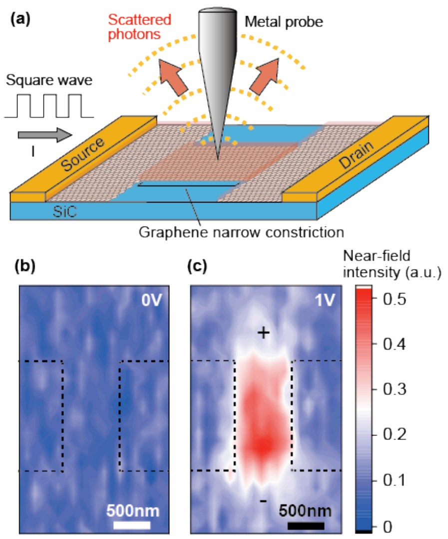

Fig. 1 (a) Schematic of the experimental configuration used to detect current-driven evanescent wave on graphene device with narrow structure. The metal probe is used to scatter the near-field component to the THz confocal microscope. Near-field images were obtained with the bias of (b) 0 V and (c) 1 V, respectively.

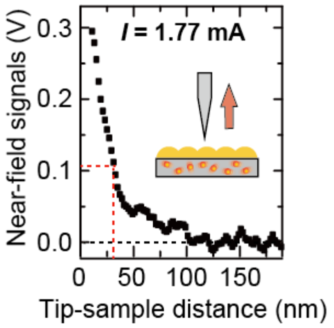

Fig. 2 Decay profile of the near-field signal with increasing the tip-height measured at the center of narrow constricted area with modulating current $I$ = 1.77.

In the graphene device, we successfully imaged current-induced excess near-field signals in epitaxial bilayer graphene with s-SNOM. As shown in Fig. 1(a), an AFM tip non-invasively probes excess noise (current fluctuation) by scattering EM evanescent waves (~20 THz) generated on the graphene layer. Figures 1(b) and 1(c) shows the 2D image of the near fields taken with the current, $I$, of 0 mA and 1.77 mA. The current-induced excess evanescent fields, shows up only in the constricted region because the current density is much higher in the constricted region than the outside region. The signal, taken at the center of narrow region with $I$ = 1.77 mA, fell to zero when the tip was raised higher than 100 nm as shown in Fig. 2. This indicates that the detected excess near field is the evanescent waves with a decay length of ca. 30 nm. When

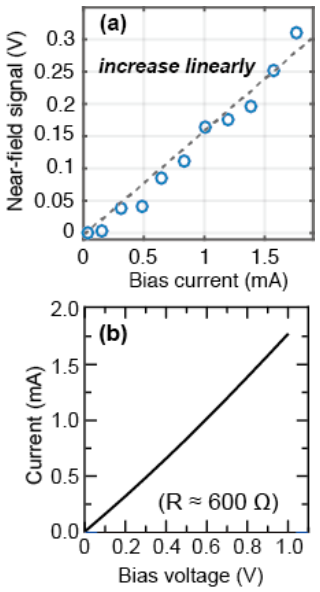

Fig. 3 (a) Near-field intensity measured on the center of the narrow constriction is found to linearly increase with bias current. (b) Current-voltage curve of the graphene device

the current density is increased, the measured excess near field increases linearly with current and shows up only in the constricted region as shown in Fig. 3(a). Basically the device was operated in the linear region as I-V curve shown in Fig. 3(b). According to the simulation, the intensity of the near-field signals consistent with the current density distribution simulated with COMSOL.

In the NiCr device with a U-shaped structure as shown in Fig. 4(a), we imaged thermally excited EM evanescent wave driven by bias current. Figure. 4(b) shows the near-field image of the NiCr device with a current density of 8.3 × $10^6$ A/cm$^2$. The hot-position in the inner part of the U-shape reveals that the current crowding effect can be observed by our THz near-field microscope. The probed near-field signal is directly related to the EM energy density of the thermal near-field radiation, which is temperature dependent. The temperature distribution is consistent with simulation by considering the Joule heating. Therefore, our THz SNOM can overcome the diffraction-limit and achieve the nanoscale spatial resolution for thermometry.

In the semiconductor GaAs 2DEG device, a narrow conducting channel with a width of 400 nm and a length of 400 nm was formed after wet etching as shown in Fig. 5(a). The I-V curve, shown in Fig. 5(b), indicates that the current passing through the device is nonlinear with increasing voltage above 2.0 V. We found the near-field signal appears in the narrow region

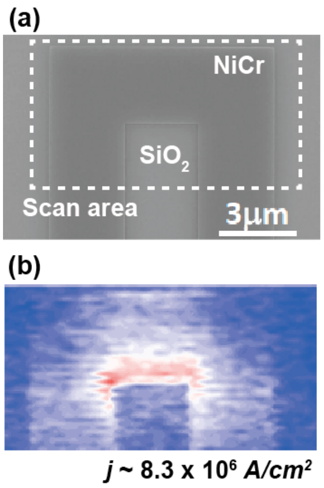

Fig. 4 (a) SEM image of the NiCr device. The width of the narrowest part is 3 μm, and the thickness is 50 nm. (b) Thermal near-field image of the NiCr device with a current density of 8.3 × $10^6$ A/cm$^2$. The localized hot-position is imaged due to current crowding effect.

while the device was biased higher than 0.5 V. In the linear region, the near-field signals are confined in the narrow region. The result indicates that the electrons gain extra energy while passing through the narrow where a high electric field exists. However, while the device

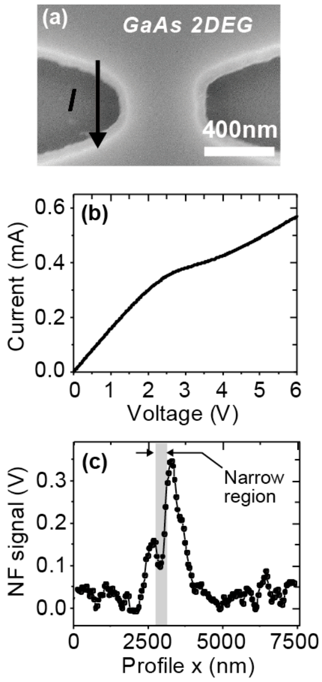

Fig. 5 (a) SEM image of the GaAs 2DEG device. (b) The solid line shows the current-voltage of the GaAs device. (c) When the device enters into the nonlinear region, two hot spots appear at front and back end of the narrow channel.

was biased into nonlinear region, an extraordinary phenomenon was observed. The two hot spots appear at the front and back end of the narrow channel as shown in Fig. 5(c). Nowadays, there are no theoretical works can explain such kind of the phenomenon of the energy dissipation. We have tried to simulate it with the Joule heating model by COMSOL simulator, but it fails to explain. For the GaAs 2DEG device, it is extremely valuable for further study in the near future.

In the project, we have performed the passive s-SNOM represents non-invasive characterization tool for the investigation of the nanoscale noise or temperature mapping in graphene, metal, and semiconductor device.

## ５．主な発表論文等

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## ６．研究組織

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